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EXPLORING THE EFFICACY OF PIEZOELECTRIC-BASED SENSORY SYSTEMS FOR HEART RATE MONITORING IN DIFFERENTIATING STRESS VS RELAX CONDITIONS

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ABSTRACT: Stress has diverse effects on human physiological reactions, and one such effect is on heart rate (HR). The established methods to acquire HR is by electrocardiogram (ECG) and photoplethysmogram (PPG). ECG electrodes need to be placed on the chest, which can cause inconvenience and is not practical in daily life, while PPG signals are known to contain more noise than ECG. Thus, this work aims to investigate the efficacy of a piezoelectric-based sensory system in measuring HR and using the signal to differentiate stressed and relaxed conditions by means of statistical analysis. Two activities were conducted to achieve the goal. The first experiment involved collecting and analysing piezoelectric signals to measure the pulse rate (*bpm*) and compare this with the HR from PPG. For the second experiment, the piezoelectric-based HR was calculated from 20 subjects (male and female, age ranging between 20 and 25) in relaxed and stressed conditions. The stress condition was triggered using two stressors: the Stroop Colour Word Test and the Digit Span Test. Statistical analyses reveal a strong positive correlation between piezoelectric-based heart rate (HR) and oximeter readings ($r(12) = 0.993$, $p < 0.001$), despite the fact that the values are not precisely identical. In addition, the findings also indicate that there are significant effects by the mental states (stressed and relaxed) on the piezoelectric-based HR readings ($p<0.05$). Employing a within-subject design condition, the results further illustrated that piezoelectric readings are elevated during stressed conditions (*Mean*±*SD* = 72.395±0.097) and diminished during relaxed conditions (*Mean*±*SD* = 71.615±0.126). Therefore, the suggested piezoelectric-based sensory system has been validated as an effective means of categorizing stress and relaxation based on heart rate signals.

ABSTRAK: Tekanan mempunyai pelbagai kesan terhadap reaksi fisiologi manusia dan satu daripadanya adalah kadar denyut jantung (HR). Kaedah biasa bagi mengetahui HR adalah melalui elektrokardiogram (ECG) dan fotofetismogram (PPG). Elektrod ECG perlu dipasang pada bahagian dada di mana boleh menyebabkan ketidakselesaan dan tidak praktikal dalam kehidupan seharian, manakala PPG mengandungi lebih banyak gangguan isyarat berbanding ECG. Oleh itu, kajian ini bertujuan mengkaji kecekapan sistem deria berasaskan piezoeletrik bagi membaca HR dan menggunakan isyarat ini bagi membezakan keadaan tertekan atau tenang melalui kaedah analisa statistik. Untuk mencapai objektif, dua aktiviti telah dijalankan. Pertama eksperimen melibatkan pengumpulan dan analisis isyarat piezoeletrik bagi mengira kadar nadi (bpm) dan membandingkannya bacaan HR daripada PPG. Eksperimen kedua, HR berasaskan piezoelektrik dikira daripada 20 subjek (lelaki dan perempuan, berumur antara 20 dan 25) dalam keadaan tenang dan tertekan. Keadaan tertekan dibuat melalui dua kaedah: Stroop Color Word Test dan Digit Span Test. Analisis statistik mendedahkan hubungkait yang kuat antara kadar denyut jantung (HR) berasaskan piezoeletrik dan bacaan oksimeter ($r(12) = 0.993$, $p < 0.001$), walaupun bacaan tidak sama sepenuhnya. Tambahan, penemuan ini menunjukkan terdapat kesan penting terhadap tahap mental (tertekan dan tenang) pada bacaan denyut jantung (HR) berdasarkan piezoeletrik ($p<0.05$). Dengan mengaplikasi kaedah within-subject, hasil menunjukkan bacaan piezoeletrik meningkat dalam keadaan tertekan (Mean±SD = 72.395±0.097) dan kurang dalam keadaan tenang (Mean±SD = 71.615±0.126). Oleh itu, system deria berasaskan piezoeletrik yang dicadangkan telah diuji berkesan untuk mengenal pasti keadaan tertekan dan tenang berdasarkan isyarat denyut jantung.

KEYWORDS: *Piezoelectric Sensor, Heart Rate, Stress Detection*

1. INTRODUCTION

The issue of mental health has become a common and significant problem in modern society. One of the major contributors to mental illness is stress. Most of the time, people are unaware of being under stress, for example, when they are occupied with deadlines for certain projects or works. This deleterious effect of stress is usually defined as the short-term sympathetic nervous system activation caused by cognitive stressors [1]. However, long-term exposure to stress can be chronic, and people may not be aware of its existence. Chronic stress can result in severe problems, including increases in blood pressure, weakening of the body's immune system, muscle pain, increased risk of heart attack and stroke, depression, etc. [2].

Numerous methods and techniques are being introduced today to detect stress. A popular method uses human physiological signals to identify stress presence as it is proven that humans will be physiologically affected under stress [3]. The most frequently used parameters for stress detection are Blood Pressure (BP) [4], Respiration Rate (RR) [5], and Heart Rate (HR) [4], [6], [7], [8]. Others include muscle activity measurement [9], temperature measurement [10], and electrodermal activity [11]. Many studies report that heart rate increases significantly during states of stress, whereas a few others did not show any significant change [4], [6], [7], [8]. This method is the most straightforward and the most used, with the vast majority being a reliable measure for the arousal part of stress [12].

Among the popular sensors to acquire HR data used are the electrocardiogram (ECG) [13], [14], [15], and the photoplethysmogram (PPG) [16], [17]. ECG is a method where electrodes need to be placed on specific locations on the body (i.e. chest, forearms, and lower leg) to capture the electrical signals of the heart. ECG requires tedious preparation to ensure the quality of the data collected as the electrodes are placed onto the skin. The area of the skin will need to be prepared well, such as to shave excessive hair that might reduce the contact between the electrodes and skin, which consequently may cause discomfort to the subjects [18].

Meanwhile PPG employs the optical method for the identification of volumetric alterations in peripheral blood circulation. A significant challenge associated with the utilization of PPG-based monitoring techniques is their limited accuracy in tracking PPG signals during everyday activities and mild physical exertion due to the susceptibility of PPG signals to Motion Artifacts (MA) induced by hand movements. In addition, external factors such as environmental noise can further impact the acquisition of PPG signals, consequently affecting the precision of heart rate estimation [19].

Both ECG and PPG are explicitly measuring the physiological signal of a body to get the HR reading. ECG electrodes need to be placed on the chest, which can cause inconvenience and is not practical in daily life, while PPG signals are known to contain more noise as compared to ECG. Another alternative that is gaining popularity is a mechanical-based sensory system, such as piezoelectric sensors.

Piezoelectric is a transducer that can assess electromechanical ability. It converts mechanical energy into electrical energy and vice versa [20]. Manipulating its electromechanical features, piezoelectric transducers are also exploited to measure one's HR. [21] analysed the efficacy of an in-ear piezoelectric-based sensory system to monitor HR and obtained promising results (i.e., 97.17% accuracy). Meanwhile, a study in [22] utilized piezoelectric ceramic sensors to measure HR and the findings showed a good accuracy as compared to an XD-58C HR pulse sensor. Another study reported in [23] measured HR via chest vibrations. These studies proved that piezoelectric sensors are reliable to be used as HR measurement. However, to the author's knowledge, none of the research conducted on investigating the HR captured by piezoelectric-based sensory systems was for stress detection application.

Therefore, this paper aims to investigate the efficacy of a piezoelectric-based sensory system in differentiating between stressed and relaxed conditions using the HR signal. The HR measurement was acquired using a piezoelectric-based sensory system, which was placed at the wrist of healthy young adult subjects. State Trait Anxiety Inventory (STAI) and psychological reactance questionnaire were used to benchmark the mental state of the subjects while performing the experiment. The data was then analysed for its consistency across the subjects and the correlation between the piezoelectric-based sensory system's data and mental health conditions (i.e., relax vs stress), which was attained via mental health score from the questionnaire.

2. METHODOLOGY

2.1. Piezoelectric-based sensory system data verification

In this study, a PVDF Piezoelectric Film with a length of 4cm (LDT1-028K) manufactured by TE CONNECTIVITY SENSOR Co., Ltd was used [24] because it has higher flexibility, higher sensitivity, and higher dynamic range. Conceptually, the heart rate can be measured by a piezoelectric sensory system by detecting the impulse that is caused by the expansion and contraction of the blood vessels near the surface of the skin. The mechanical pounding sensed by the piezoelectric sensor is then converted into an electrical signal and analysed to measure the HR [25]. In this study, the voltage signal from the sensory device was acquired using Arduino Uno.

The piezoelectric sensor measurement shown in Fig. 1 was compared with a PPG-based device (i.e., oximeter) to verify the reliability of the sensory system developed. Fig. 2 shows the experiment setup to check the reliability of the sensor. The piezoelectric sensory device is worn on the wrist, while the oximeter is worn on the same hand's finger. Both devices are worn on the non-dominant hand.

The voltage signal from the piezoelectric (Fig. 3) is acquired using the Arduino analog input and used in calculating the HR measurement using the formula in Eq. 1:

$$Heart\ Rate\ (in\ bpm) = \frac{60}{Time\ interval\ between\ two\ peaks\ (in\ seconds)} \quad (1)$$

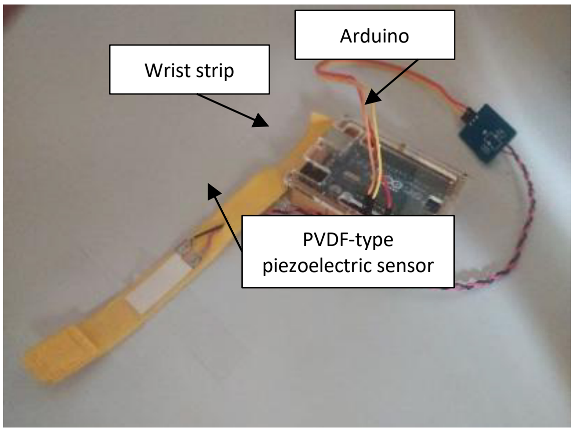

Figure 1. Piezoelectric-based HR measurement device used in this study.

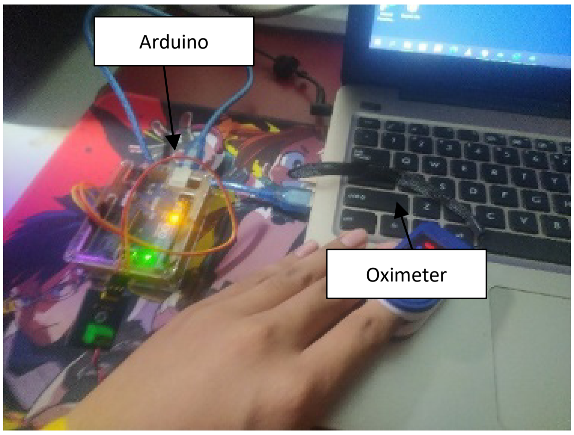

Figure 2. Set-ups to test the reliability of the sensors

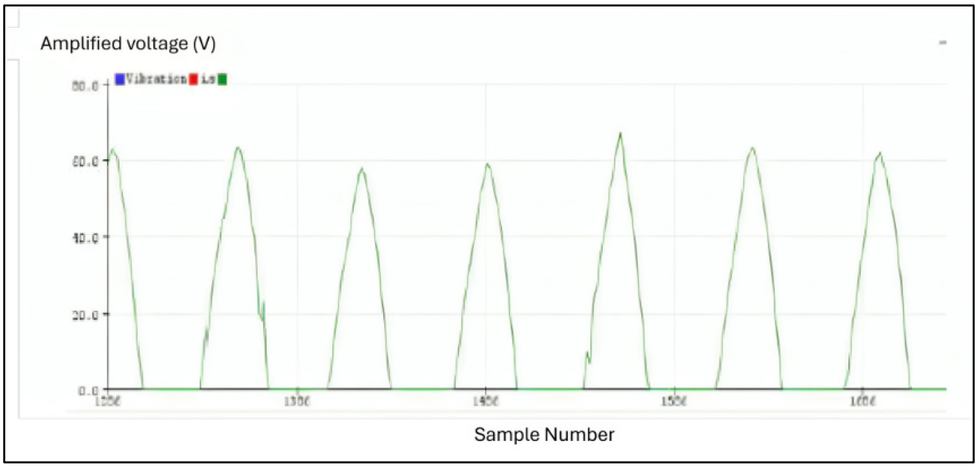

Figure 3. Example of the voltage signal produced by the piezoelectric sensor to measure pulse.

Since the aim of this experiment is to benchmark the developed sensory system with the established PPG-based sensor (i.e., oximeter), the HR readings were recorded from both sensors during resting and active conditions from two subjects. During the active state, the subject was asked to perform jump roping for one minute, and their heart rate was recorded using the two devices mentioned above. At the same time, for rest condition, the measurement was taken while the subjects were in a relaxed sitting position. Six measurements, each for relaxed and active conditions, respectively, made a total of twelve samples for relaxed and another twelve samples for active.

2.2. Piezoelectric-based sensory system efficacy in stress detection.

This section explains the procedures taken to investigate the developed sensory system efficacy in differentiating mental states (i.e., relaxation vs stress).

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2.2.1. Experiment Setup

For this work, 20 subjects were recruited, consisting of 10 males and 10 females, ages ranging from 20 to 25. All subjects were students at IIUM and physically healthy. Their participation in this study was voluntary, and consent forms were given and signed before starting the experiment. As this investigation primarily aimed to evaluate the capability of the implemented sensory system in distinguishing between stressed and relaxed mental states, the inclusion of diverse age groups and other variables was deemed unnecessary at this stage. Therefore, this study's selected cohort of subjects was regarded as adequate for achieving the specified objective.

The experiment was conducted in a controlled environment without outside interference. As illustrated in Fig. 4, it was conducted in a room that was covered by a black curtain to isolate the subject from others in the Biomechatronics Research Lab, IIUM.

White light was selected for the room to prevent the light from affecting the subject's mental conditions. Furthermore, the room was equipped with air conditioning to ensure the comfort of the subjects throughout the duration of the experiment. This research work has obtained ethics approval from the IIUM Research Ethics Committee (IREC 2022-044).

Figure 4. Setup of the experiment

2.2.2. Experiment Procedure

The experimental setups are designed to repeatedly place the subjects in states of emotional and cognitive discomfort. This is done to compare the differences in piezoelectric readings when the subjects are stressed or relaxed.

The data collection process for the mental condition involved a five-phase experiment (i.e., stress or relax). The phases are known as “First Relax Phase” (R1), “First Stress Phase” (S1), “Second Relax Phase” (R2), “Second Stress Phase” (S2), and “Last Relax Phase” (R3).

During the experiment, the subjects were placed in a quiet environment without any outside distractions. They were instructed to wear headphones and a piezoelectric sensor on their wrists. The music "Weightless" by the Macaroni Union was selected for every relax phase based on a research discovery [26] that indicated that it might lower anxiety and encourage relaxation. This procedure was critical for determining each subject's baseline since physiological measurements show a wide range of variation across all subjects [11].

In the stress phases, two stressors were used to induce stress among the subjects, namely the Stroop Colour Word Test (SCWT) and Digit Span Test (DST). The SCWT requires the subjects to concentrate between the words and the colour of the words while the DST requires the subjects to memorize a number or digit's arrangement and reproduce the same sequences back. During this phase, the subjects were requested to listen to a piece of hardcore background music throughout their experiments. Loud music can induce stress in humans [27]. Each subject was equipped with noise-canceling headphones to make sure they were fully immersed in the music provided during the experiment.

Each of the phases took five minutes duration. In total, each subject spent approximately 25 minutes to complete the whole experiment procedure and data was taken for only one cycle for each subject. The HR was calculated for every 30s for each subject. Therefore, the accumulated measurement for all 20 subjects comprised 600 for the relaxed condition and 400 for the stressed condition. For every completed phase, the subjects were asked to fill in the questionnaire detailed in Section 2.2.3.

2.2.3. Questionnaire

For the mental health score, subjects were asked to fill in questionnaires consisting of STAI (State-Trait Anxiety Inventory) [28] and psychological reactance [29] questions at the end of each phase. Both questionnaires were the standard quantitative measurement that is used to identify traits and states of anxiety [30].

2.3. Statistical Package for Social Science (SPSS) Analysis

The data accumulated from the questionnaires were analysed using the Statistical Package for Social Science (SPSS). A repeated measure of Analysis of Variance (ANOVA) was utilized to compare the mental pressure score and piezoelectric reading under rest and stress situations, and Cronbach's alpha measurement was used to test the reliability of the data. A correlation test was also conducted to find the correlation between the variables.

The analysis for this work was based on four hypotheses, which were:

- Hypothesis 1: There is a significant difference between phases (R1, S1, R2, S2 and R3) on the mental pressure score from the questionnaire.
- Hypothesis 2: There is a significant difference between conditions (Relax & Stress) on the piezoelectric reading.
- Hypothesis 3: There is a significant difference between phases (R1, S1, R2, S2 and R3) on the piezoelectric reading.
- Hypothesis 4: There are positive correlations between mental pressure scores and piezoelectric readings between phases.

3. RESULTS AND DISCUSSION

3.1. Piezoelectric-based reading vs oximeter HR measurement

The experiment in Section 2.1 was conducted to check the relationship between piezoelectric readings and the heart rates measured using an oximeter. The tabulated results are presented in Table 1.

Based on the data, it can be observed that the value of the piezoelectric-based heart rate and the oximeter were not exactly within the same range, with the bpm obtained by the piezoelectric sensors being lower than those measured by the oximeter. Among the possible factors of the discrepancy are the resolution of the DAQ device used and the signal processing methods used in determining the peak-to-peak time intervals.

Table 1. The tabulated data for piezoelectric and oximeter data.

Sub	N	Rest		Stress	
		Piezo	*Oximeter*	*Piezo*	*Oximeter*
1	1	72	95	78	131
	2	72	97	76	119
	3	71	90	79	135
	4	72	97	78	130
	5	71	93	76	126
	6	70	89	79	137
2	1	72	94	78	130
	2	72	97	76	123
	3	71	91	79	134
	4	72	99	78	132
	5	71	93	76	126
	6	70	89	79	137

However, given that the primary objective of this study was to assess the viability of employing a piezoelectric sensor for classifying an individual's stress levels (i.e., stress versus relax), an exact match in heart rate values was not essential. What remained crucial was a strong correlation between all readings obtained from the same sensor device and the measurements derived from the oximeter.

Therefore, a statistical analysis was conducted using the collected data to quantify the strength of the linear relationship between the oximeter and piezoelectric-based HR measurement. The One-Tailed Pearson's Correlation Test was performed using SPSS, and the result showed that there was a high positive correlation between the piezoelectric reading and the oximeter reading, $r(12) = 0.993$, $p < 0.001$. This implies that as the oximeter value rose, the piezoelectric value similarly increased, thereby allowing the piezoelectric-based heart rate's current reading to be employed for mental condition analysis in a manner analogous to the oximeter.

3.2. Piezoelectric-based sensory system efficacy in stress detection

3.2.1. Mental Health Score via Questionnaire

Fig. 5 shows the mean and standard deviation of the STAI-6 score and psychological reactance questionnaire. Meanwhile, Fig. 6 illustrates the estimated marginal mean for each phase (i.e., R1, S1, R2, S2, R3) collected from 20 subjects. It can be observed from the graph that, in general, the data was consistent based on the low standard deviation value for all phases. Another outstanding observation that can be made from Fig. 5 and 6 is that both stress phases (S1 and S2) yielded a higher score for all subjects than the relax phases. The mean score for S1 and S2 is 2.76 ($SD = 0.78$) and 2.80 ($SD = 0.68$), respectively (Fig. 6); meanwhile, all relax phases yielded an average score below 2.0 (SD= 0.63), as demonstrated in Fig. 7.

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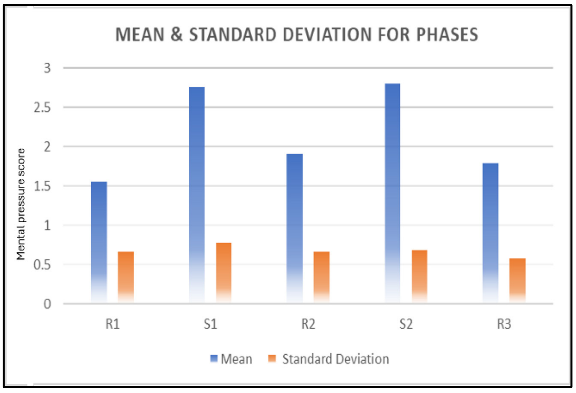

Figure 5. Mean & standard deviation for each phase of mental pressure score from STAI-6 and psychological questionnaire.

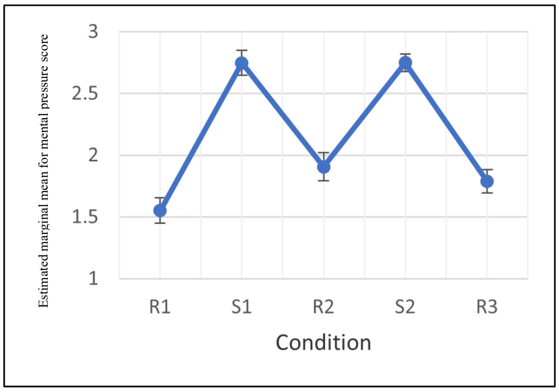

Figure 6. Estimated marginal mean of the effect of phases on mental pressure score from STAI-6 and psychological questionnaire.

An ANOVA test was performed to test Hypothesis 1 of this research. Results indicate that there were significant effects of phases (R1, S1, R2, S2, and R3) on the physiological signal, $F(4,16) = 44.856$, $p < 0.001$, partial $\eta 2 = 0.918$.

Hence Hypothesis 1 was accepted and therefore, the questionnaire score became the benchmark to indicate the real condition (i.e., relax or stress) of the subjects for the later experiments.

3.2.2. Piezoelectric Reading vs Mental Conditions

After the sensory system was developed, data from 20 volunteer subjects were analysed to investigate the reliability of the collected data and the efficacy of the piezoelectric-based HR measurement to differentiate relaxed and stressed conditions via statistical means. Fig. 7 illustrates the *Mean* ± *SD* of the piezoelectric-based HR measurement for all subjects with respect to time.

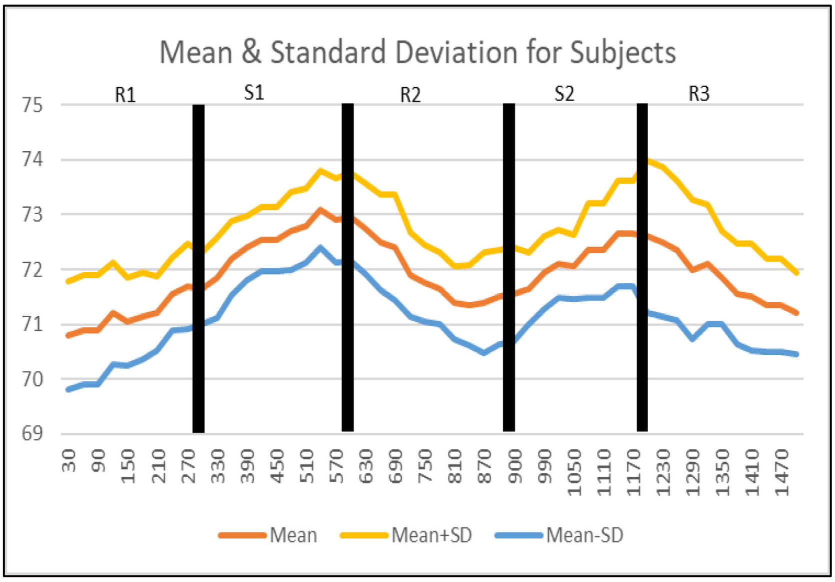

Figure 7. Mean ± SD of the piezoelectric-based HR measurement of 20 subjects.

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Cronbach's Alpha test was conducted to confirm the reliability of the data. It is the most common measure of internal consistency, and it is known as reliability. The findings indicate that data obtained from the piezoelectric sensor demonstrated a high level of reliability during both the relaxation (R1, R2, and R3) and stress (S1 and S2) phases, with coefficients of internal consistency of (30 readings; $\alpha = .942$) and (20 readings; $\alpha = .871$), respectively.

3.2.3. Piezoelectric readings and mental condition (R1, S1, R2, S2, and R3) correlation

ANOVA tests were performed to confirm Hypotheses 2 and 3 of this research.

Hypothesis 2: There is a significant difference between conditions (Relaxed vs. stressed) on the piezoelectric reading.

Repeated one-way measures of the ANOVA test were used for the effect toward the physiological signal with stress and relaxation as the independent variable and physiological signal as the dependent variable. The result shows that there is a significant effect of condition (relaxed and stressed) on the physiological signal, $F(1,19) = 80.953$, $p < 0.001$, partial $\eta^2 = 0.810$, thus proving Hypothesis 2 was accepted. Bonferroni Post Hoc Tests showed that subjects measured the lowest piezoelectric reading in the relax phase ($M = 71.615$, $SD = 0.126$) and the highest happened in the stress phase ($M = 72.395$, $SD = 0.097$). This outcome is in accordance with the findings of many other works summarized by [31], in which 18 out of 23 studies found that HR increases when a person is under stress.

To conclude this, when the subjects were in the relax phase, the sensor reading was lower, and when the subjects were in the stress phase, the sensor reading was higher. It shows that the piezoelectric sensor could distinguish between the relaxed and stressed conditions. Fig. 8 shows that the piezoelectric readings were lower in the relaxed condition and higher in the stressed condition. Hence, the results depict that the subjects were in the appropriate emotional and mental health situation as desired.

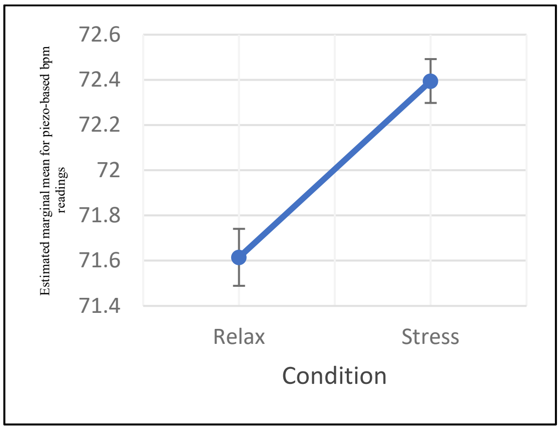

Figure 8. Estimated marginal mean of the effect of conditions on piezoelectric reading

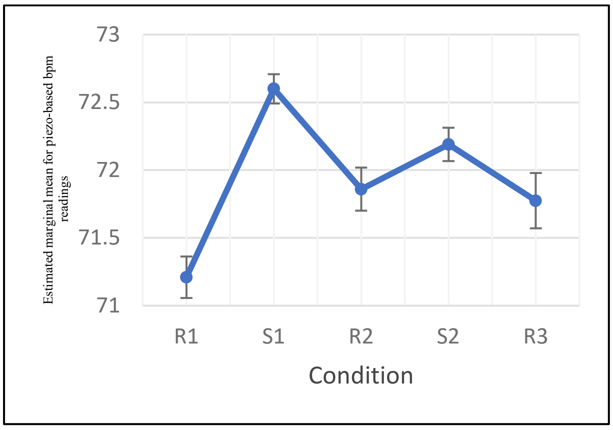

Figure 9. Estimated marginal mean of the effect of phases on piezoelectric reading

Hypothesis 3: There is a significant difference between phases on piezoelectric reading.

A repeated one-way measure of the ANOVA test was also used to measure the effect on the physiological signal, with phase as the independent variable and physiological signal as the dependent variable. As results, there were significant effects of phase (R1, S1, R2, S2, and R3) on the physiological signal, $F(4,16) = 24.504$, $p < 0.001$, partial $\eta^2 = 0.860$. Hence Hypothesis 3 was accepted. The linear test of within-subject contrast indicates a significant relation between independent and dependent variables, $F(4,76) = 80.953$, $p < 0.001$, partial $\eta^2 = 0.810$. Fig. 9 illustrates that all relax phases (R1, R2, and R3) were relatively lower than stress phases (S1 and S2), and S1 ($M = 72.600$, $SD = 0.108$) displayed a higher marginal mean as compared to S2 ($M = 72.190$, $SD = 0.123$).

3.2.4. Piezoelectric readings and questionnaire findings correlation

Hypothesis 4: There are positive correlations between mental pressure score and piezoelectric reading between phases.

To confirm the hypothesis, a correlation test was run using SPSS to determine the correlation between the mental pressure scores for each relaxed and stressed condition. Table 2 tabulates the Pearson's correlation, *r*-value and significance, *p*-value by comparing piezoelectric readings with respect to phases (1st row) with questionnaire score with respect to phases (1st column).

Table 2: Correlation test results between piezoelectric readings and mental pressure score from questionnaire. (Note: 1st column refers to the labels for phases with respect to the questionnaire, while 1st row refers to phases with respect to piezoelectric reading)

	R1_piezo	**S1_piezo**	**R2_piezo**	**S2_piezo**	**R3_piezo**
R1_Ques	$r(20)=0.595$, $p<0.01$	Not significant	Not significant	$r(20)=0.436$, $p<0.05$	Not significant
S1_Ques	Not significant	Not significant	Not significant	Not significant	Not significant
R2_Ques	Not significant	Not significant	Not significant	Not significant	Not significant
S2_Ques	$r(20)=0.544$, $p<0.01$	$r(20)=0.401$, $p<0.05$	$r(20)=0.453$, $p<0.05$	Not significant	Not significant
R3_Ques	$r(20)=0.396$, $p<0.05$	Not significant	Not significant	$r(20)=0.404$, $p<0.05$	Not significant

From the table, only R1 shows a high correlation between the piezoelectric reading and the questionnaire's mental score (r(20)=0.595, p<0.05), while the rest do not show a high correlation between both methods. However, some correlation can be detected across relax-relax or stress-stress phases. S2_Ques shows significant correlation with S1_piezo ($r(20)=0.401$, $p<0.05$), and R3_Ques is correlated to R1_piezo ($r(20)=0.396$, $p<0.005$).

It can also be observed that there are significant correlations between stress-relax conditions in the table. For instance, S2_Ques is seen to be highly correlated with R1_piezo and R2_piezo. One viable factor is the carried-over effect from the previous phase, hence affecting the subject's answers in the questionnaire.

Nevertheless, these findings prove that piezoelectric readings are correlated to mental condition (i.e., stress and relax), but may not accurate enough to relate data from both methods of a specific phase (e.g., S1 to S1).

4. CONCLUSIONS

This study's goal is to show the feasibility of detecting stress by changes in HR using a piezoelectric-based sensor. Twenty subjects were recruited to investigate the feasibility of the proposed sensory system.

This project successfully designed a piezoelectric-based sensory system to detect the stress level of a human using a piezoelectric sensor. Although the data that was retrieved by the piezoelectric sensor was not the same as the reading from the oximeter (that used a different sensing method), there was nonetheless a high positive correlation between the two of them (p-value < 0.01).

In addition, the data obtained from SPSS analysis aligned remarkably with the phase involved. High mental pressure scores were found in the stress phase, which was the target of that phase, while low mental pressure scores were found in the relax phase, aligning the phase and piezoelectric readings of the phase involved. Hence, it can be concluded from the findings that a piezoelectric-based sensor is feasible to obtain heart rate projection and consequently distinguish between relaxed and stressed conditions.

Importantly, the sensory system developed in this study can be further improved to yield better performance. In the future, a classification algorithm shall be developed to categorize stressed vs relaxed based on piezoelectric data. A study to check the feasibility of the proposed sensory system in detecting different levels of stress is also recommended. In addition, the number of subjects with varying BMIs must also be added to increase the robustness of the data collected. Hence, there is a need for the introduction of newer, more compact, and ergonomically designed piezoelectric-based sensors in the future. This step will facilitate convenient comparisons with the outcomes presented in this project.

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